

locyanine thicknesses that result in the low-resistance electrical contact. By properly controlling the ITO sputter deposition process so as to control the degree of damage caused at the surface, a cathode/organic layer interface can be produced having the desired low resistance. As described elsewhere herein, it is believed that the reduced barrier to electron transport, as evidenced by the low-resistance electrical contact, is provided by a high density of surface states at or near the surface of the organic layer. Still other methods that include the step of introducing a high density of surface states to form a cathode having a low-resistance contact between an electrically conductive non-metallic layer and a semiconductive organic layer also fall fully within the scope and spirit of the present invention.

[0051] It is believed that this feature of the present invention, that is, the ability to form a highly efficient electron-transporting cathode/organic layer interface, comparable to low-work-function metallic materials, but without the high reflectivity of metallic materials, is a uniquely advantageous combination of properties not possessed by the previously known cathode materials that were used in organic optoelectronic devices. Thus, while the present invention is described herein in terms of a specific representative embodiment thereof, it is believed that the scope and spirit of the present invention embraces any cathode comprised of an electrically conductive non-metallic layer which forms a low-resistance electrical contact with a semiconductive organic layer. Furthermore, it is believed that any method which comprises preparing surface states having a sufficiently high density to substantially reduce the barrier to electron flow between an electrically conductive non-metallic material and a semiconductive organic layer also falls fully within the scope and spirit of the present invention. A substantial reduction in the barrier to electron flow is specified herein as a reduction that results in the formation of a low-resistance electrical interface, as defined herein, between the electrically conductive non-metallic layer and the semiconductive organic layer of the cathode/organic interface. Thus, the present invention is directed to a method for fabricating a cathode comprising preparing an interface having an electrically conductive non-metallic material on one side of the interface and a semiconductive organic material on the opposite side of the interface, wherein the preparation step includes the step of forming any intermediate region between the electrically conductive non-metallic material and the semiconductive organic material such that the electrically conductive non-metallic material is capable of functioning as a cathode that forms a low-resistance electrical contact with the semiconductive organic material.

[0052] Use of electrically conductive non-metallic cathode materials that do not have the highly reflective properties inherent for metallic materials generally provides the specific benefit of being able to select highly transparent materials for use as the cathode in devices for which high optical transmission is desired, in particular, in optoelectronic devices such as OLEDs. One of the further features of the present invention is, thus, that optoelectronic devices such as OLEDs may be made using highly transparent non-metallic cathodes with electron-injection properties comparable to semi-transparent metallic cathodes. As compared with the thinnest practical semi-transparent metallic cathodes, which may typically provide a maximum transmission in the overall device of about 60-70%, devices

having an optical transmission of at least about 85% may be prepared using the non-metallic cathodes of the present invention.

[0053] The electrically conductive non-metallic material that may be used to prepare the cathodes of the subject invention may be selected, for example, to be a transparent wide band gap semiconductor, for example, wide band gap semiconductor having a band gap of at least 1 eV and a transmission of at least 50% for incident and admitted radiation. Preferred wide band gap semiconductors include conductive oxides such as ITO, tin oxide, or gallium indium tin oxide (GITO).

[0054] The semiconductive organic materials that may be effectively used in combination with the ITO layer to produce the efficient electron injection preferably have the following properties:

[0055] 1. A chemical and structural stability that is sufficient to permit only limited damage, as described hereinafter, due to sputtering during deposition of the ITO layer. Large planar molecules such as phthalocyanines, naphthalocyanines and perylenes are representative examples. Derivatives of these compounds with further extended conjugation (e.g., additional fused benzo-, naphtha-, anthra-, phenanthrene-, polyacene, etc., groups) may also be used. Polymeric materials may also be present under certain circumstances.

[0056] 2. An electron mobility that is sufficient to permit the layer to function as an electron transporting layer; an electron transporting material having a carrier mobility with a value of at least 10^{-6} cm²/Vsec is generally believed to be sufficient for a material to function as an electron transporting layer, though substantially higher values are generally preferred; once again, large planar molecules such as the phthalocyanines and certain perylenes are representative examples.

[0057] 3. The difference between the ionization potential (IP) and the HOMO/LUMO gap energy (the energy gap between the highest occupied molecular orbital and the lowest unoccupied molecular orbital), that is, the "IP-HOMO/LUMO gap energy", of the material used in the electron injecting interface layer is such that it is approximately equal to or preferably less than the IP-HOMO/LUMO gap energy of the film into which electrons are being injected. This guideline is not intended as a constraint that is to be strictly obeyed, but is instead intended to be approximately followed. For example, small deviations from this guideline of about 0.5 eV may be tolerated for certain combinations of materials. Use of this guideline helps to prevent formation of an energy barrier to electron flow into the contacted film (e.g. Alq₃).

[0058] Still more specifically, the subject method may be comprised of using ITO as the electrically conductive non-metallic layer and a phthalocyanine such as CuPc or ZnPc as the electron injecting interface layer. In this case, the electrically conductive non-metallic ITO layer is sputter deposited onto an organic protection layer comprised of the electron injecting interface layer of CuPc or ZnPc. So as to control the level of damage, the ITO is sputtered onto the organic layer at relatively low initial deposition rates of